fibers

MDPI

Article

Wearing Quality of Ribbed Knits Made from Viscose and Lyocell Fibers for Underwear

Antoneta Tomljenović [1,*], Juro Živičnjak [1] and Zenun Skenderi [2]

[1] Department of Materials, Fibers and Textile Testing, University of Zagreb Faculty of Textile Technology, Prilaz baruna Filipovića 28a, 10000 Zagreb, Croatia; juro.zivicnjak@ttf.unizg.hr

[2] Department of Textile Design and Menagement, University of Zagreb Faculty of Textile Technology, Prilaz baruna Filipovića 28a, 10000 Zagreb, Croatia; zskenderi55@gmail.com

* Correspondence: antoneta.tomljenovic@ttf.unizg.hr

Abstract: As an alternative to cotton, viscose and lyocell fibers are suitable for the production of knitted next-to-skin underwear. Despite the advantages of a more environmentally friendly production process and valuable properties, the consumption of lyocell fibers is significantly lower compared to viscose fibers. The applicability of viscose and lyocell fibers in the production of ribbed knits for underwear is insufficiently researched, as is the influence of unconventionally spun yarns on their wearing properties. This study, therefore, investigates the possibilities of using lyocell fibers in the production of novel knitwear with improved properties compared to viscose and conventional cotton knitwear and determines their wearing quality. In this context, two sets of circular 1 × 1 rib jersey fabrics were produced from three types of differently spun viscose and lyocell yarns. The quality of the dry relaxed and wet processed knitted fabrics was evaluated by determining their structure, absorbency, air permeability, and dimensional stability, as well as their tensile, abrasion, and pilling properties, all in comparison to cotton knitted fabric produced under the same conditions. The results showed that lyocell rib knits have better structural uniformity, tensile properties, dimensional stability, air permeability, lower abrasion resistance, and comparable moisture absorbency and pilling propensity compared to viscose knits.

Keywords: knitwear; rib jersey; viscose; lyocell; yarn type; wearing quality

Citation: Tomljenović, A.; Živičnjak, J.; Skenderi, Z. Wearing Quality of Ribbed Knits Made from Viscose and Lyocell Fibers for Underwear. *Fibers* **2024**, *12*, 83. https://doi.org/10.3390/fib12100083

Academic Editor: Damien Soulat

Received: 21 August 2024
Revised: 25 September 2024
Accepted: 27 September 2024
Published: 30 September 2024

1. Introduction

Among natural fibers, cotton has the highest production, with 25 million tons per year [1]. Although cotton is the preferred natural cellulosic fiber, it has a relatively strong negative impact on the environment, mainly due to excessive water consumption, soil depletion, eutrophication, and ecotoxicity [2].

As an available alternative to cotton, the consumption of cellulose-dissolving pulp for the production of artificial fibers is expected to increase [3]. Man-made cellulose artificial fibers are fabricated using two industrially dominant technologies: the viscose and lyocell processes [4]. The viscose process involves the chemical modification of cellulose with hazardous carbon disulfide under strongly alkaline conditions, followed by its dissolution and regeneration under strongly acidic conditions [5]. The ecologically more sensible lyocell process is a direct dissolving process without the formation of a cellulose intermediate (e.g., Lyocell® process), in which N-methylmorpholine-N-oxide (NMMO) is used as a direct cellulose solvent. The lyocell process has the advantage of avoiding toxic chemicals and is based on the recycling of NMMO, resulting in less waste water and making the process more environmentally friendly [3,6].

Viscose and lyocell fibers differ in their structure and properties due to the different production methods and the rheological properties of the resulting cellulose solution during spinning. There are considerable differences in cross-section: viscose fibers have a very irregular lace shape, while lyocell fibers are roughly circular [4,7]. The properties of viscose and lyocell fibers compared to cotton are listed in Table 1. Despite the fact that only lyocell fibers have a sufficiently high tenacity comparable to that of cotton fibers, the lyocell process cannot currently replace the conventional viscose process, mainly due to the cost of the process and the nature of the fibrillating fibers produced [8]. Therefore, the conventional viscose process still dominates the industrial production of man-made fibers from cellulose, with a share of 80%, lyocell fibers with only 4%, acetate (about 13%), modal fibers (about 3%), and cupro fibers (about 0.2%) [9].

Table 1. Properties of cotton, viscose, and lyocell fibers [3,7,10–13].

Cellulosic Fiber	Viscose	Lyocell	Cotton
Cellulose degree of polymerization	290–320	550–650	2000–3000
Crystallinity	0.39	0.62	0.74
Density (g/cm^3)	1.50	1.52	1.54
Regain (%)	12–14	11–13	7–9
Water retention (%)	85–100	60–75	38–55
Elongation, dry (%) Elongation, wet (%)	17–25 21–23	10–17 17–19	7–10 12–14
Tenacity, dry (cN/tex) Tenacity, wet (cN/tex)	20–27 10–15	35–42 26–38	24–36 26–40

Viscose and lyocell fibers are suitable for the manufacture of a wide range of textile products, particularly knitted next-to-skin underwear, which is characterized by its silky feel and outstanding sorption and comfort properties [14].

Knitted fabrics, whose structure ensures the elasticity and extensibility of knitwear, are generally used for various types of underwear (e.g., underpants, undershirts, T-shirts, pajamas, nightgowns, and bathrobes) [15,16]. Weft-knitted underwear is usually made from cotton, modal, or viscose fibers in plain single jersey, but there are also various ribbed patterns (the 1 × 1 rib pattern being the most common) [17].

The knitted fabric used for underwear must be of high quality. The dimensional and structural parameters of knits, as well as the wet finishing processes, have a direct influence on the mechanical and physical properties and are therefore closely related to the wearing properties of knitwear [18]. However, knitted fabrics are susceptible to changes during use in the form of reduced visual smoothness of the surface (due to abrasion and pilling) [16] and deformation (shrinkage during washing and stretching when worn) [18,19]. Therefore, knitwear should be made from balanced fabrics,dry relaxed after knitting, and then wet processed for full relaxation [18,20] to reduce this phenomenon.

The wearing quality of knitted fabrics is strongly influenced by the origin of the fibers and the type of yarn used for their production [14,21]. It has been found that lyocell fibers shrink only slightly in water despite high moisture absorption, and Tencel® fabrics and garments are more stable when washed [22]. When comparing the dimensional differences between knitted plain single jersey made from open-end rotor yarns and conventional ring-spun yarns, the fabric made from open-end rotor yarns showed relatively better dimensional stability [23]. Fabrics made from air-jet spun yarns are less susceptible to surface pilling, and knits made from ring-spun yarns with higher tenacity have better abrasion resistance [24].

There are numerous studies that deal with the quality of weft-knitted fabrics made from cotton and/or various cellulose man-made fibers (e.g., viscose, bamboo, modal, lyocell) by investigating their specific properties. They mainly refer to the structural parameters and physical properties [21,25], the mechanical properties [15,26,27], and the wearing properties, such as dimensional stability [16,18,19,28], abrasion resistance, and pilling properties [26,29], moisture management and air permeability [30,31], as well as thermal properties [17,32–35].

A review of the literature revealed fewer comparative analyses of the properties of knitted fabrics produced from artificial cellulose fibers. Viscose, modal, and lyocell single jersey fabrics with three levels of loop lengths were tested under dry, wet, and fully relaxed conditions [36]. Compared to viscose and modal fabrics, it was found that lyocell knitted fabrics have better dimensional properties, higher bursting strength, course and wale spacing, and lower spirality. The influence of Tencel/cotton blends on the properties of single jersey knitwear compared to bamboo, modal, micromodal, and cotton was also investigated [22]. After wet processing, the results showed that 67% Tencel^{LF}/33% cotton has higher bending stiffness and higher retraction force than 67% Tencel^{STD}/33% cotton, while 67% Tencel^{STD}/33% cotton has better durability in the burst test; blending cotton with Tencel^{LF} in a 50/50% ratio improves the UV protection factor of the fabrics.

Usually, tests were carried out on single jersey knits, but other weaves were also analyzed, such as rib, interlock, and pique, mostly made of cotton. It should be noted that the relationship between the properties of viscose and lyocell yarns and the wearing properties of rib knit fabrics has not been sufficiently investigated in the literature.

Many researchers have investigated the influence of the yarn spinning system on the quality parameters of cotton plain jersey knitted fabric [37–39], but less frequently on viscose [40,41], modal [42], or their comparative analysis [43]. However, the applicability of unconventionally spun yarns in knitting rib knitwear from viscose and lyocell fibers and their wearing quality has not yet been sufficiently researched.

Knowing that the elasticity and lateral extensibility of knitted fabrics with a 1 × 1 rib pattern are higher than those of knitted fabrics made of plain jersey [44], the force-elongation diagram was previously analyzed to determine the elastic areas responsible for the behavior of viscose, modal, and Tencel™ knitted fabrics [45]. The yarn material was found to influence the elastic area of dry relaxed knitted fabrics made of different yarn structures in the course direction, with the highest elastic area achieved with ring-spun yarns, followed by air-jet and open-end rotor-spun yarns.

Despite the advantages of a more environmentally friendly production process and very valuable properties, the consumption of lyocell fibers is significantly lower than that of viscose fibers. A review of the literature revealed that the applicability of viscose and lyocell fibers in the production of rib knitwear for underwear is insufficiently researched, as is the influence of unconventionally spun yarns on their wearing properties. The aim of this study is therefore to investigate the possibilities of using lyocell fibers in the production of novel knitwear with improved properties compared to viscose and conventional cotton knitwear and to determine their wearing quality. In this context, two sets of circular 1 × 1 rib jersey fabrics were made from three types of differently spun viscose and lyocell yarns. The quality of the dry relaxed and wet processed knitted fabrics was evaluated by determining their structure, absorbency, air permeability, and dimensional stability, as well as their tensile, abrasion, and pilling properties, all in comparison to knitted cotton fabric produced under the same conditions.

2. Materials and Methods

2.1. Rib Knits Fabrication

Two sets of circular weft-knitted fabric, consisting of 1 × 1 rib courses so produced that single wales of face stitches alternate with single wales of reverse stitches, were knitted from three types of single differently spun viscose (Cv) and lyocell yarns (Cly)—ring (RI), open-end rotor (RO), and air-jet (AI). All yarns were spun in the spinning mill in Klanjec, Croatia, from bright viscose and Tencel™ staple fibers with a fineness of 1.3 dtex and a length of 38/40 mm. A detailed quality assessment of the yarns with a nominal count of 20 tex, including the properties of twist, tensile strength, and unevenness, has already been published [14]. The basic properties of the viscose and lyocell yarns used are listed in Table 2.

Table 2. Basic properties of viscose (Cv) and lyocell (Cly) differently spun yarns (RI—ring, RO—open-end rotor, AI—air-jet) [14].

Single-Spun Yarn	Count, tex	Twist, m^{-1}	Tenacity, cN/tex	Hairiness	Irregularity, %
RI-Cv	19.9 ± 0.13	751 ± 12.00	16.80 ± 1.26	6.47 ± 0.25	11.50 ± 0.18
RO-Cv	20.1 ± 0.15	rotor speed 753	13.98 ± 0.26	4.36 ± 0.08	14.63 ± 0.10
AI-Cv	20.2 ± 0.14	air pressure 0.6 MPa	14.52 ± 1.42	3.75 ± 0.21	13.31 ± 0.37
RI-Cly	20.1 ± 0.28	810 ± 14.60	26.86 ± 2.02	6.50 ± 0.21	12.21 ± 0.10
RO-Cly	19.8 ± 0.32	rotor speed 753	19.07 ± 2.11	4.73 ± 0.14	14.77 ± 0.31
AI-Cly	20.2 ± 0.30	air pressure 0.6 MPa	25.26 ± 1.88	3.53 ± 0.05	11.93 ± 0.20

Six different 1 × 1 rib jersey fabrics made from single viscose or lyocell yarn, including the cotton (Co) knitted fabric made from single ring-spun yarn with a count of 20 tex, were fabricated under the same conditions—using a double bed circular knitting machine with an E17 gauge, eight knitting systems, and a needle bed diameter of 200 mm (including 432 × 2 needles). The working speed of the cylinder was 60 rpm. The tensile force when feeding the yarn onto the knitting machine was 3 ± 1 cN on average.

During the knitting process, the yarns that make up the fabric are constantly under tension, and when the fabric is removed from the machine, it needs time to relax [18]. The knitted fabrics were therefore dry relaxed after knitting and then wet processed to stabilize and balance their dimensions. For dry relaxation, the knitted fabrics were removed from the machine and left to lie freely on a flat surface for approx. 96 h in a standard atmosphere with a temperature of 20 ± 2 °C and a relative humidity of 65 ± 4%.

The wet processing comprised washing in a bath at an initial temperature of 40 °C with the addition of 1 g/L wetting agent for 15 min; further adding hydrogen peroxide (2 g/L) and stabilizer (2 g/L) at 95 °C for 45 min at pH 10.5; then rinsing with hot water for 10 min at 80 °C; cold rinsing with acetic acid for 10 min until neutral pH; softening with silicone softener (2% of the fabric weight); drying at a temperature of 150 °C with a throughput speed of 0.15 ms^{-1} through the dryer; and finally, conditioning for 24 h under standard atmospheric conditions according to EN ISO 139:2005/A1:2011 [46].

2.2. Rib Knits Wearing Quality Evaluation Methodology

In order to determine the influence of fiber type, yarn type, and degree of relaxation on the wearing quality of knitwear, dry relaxed and wet processed viscose and lyocell rib jersey knitted fabrics were evaluated in comparison to reference cotton knits.

The design of the experiment is shown in Figure 1.

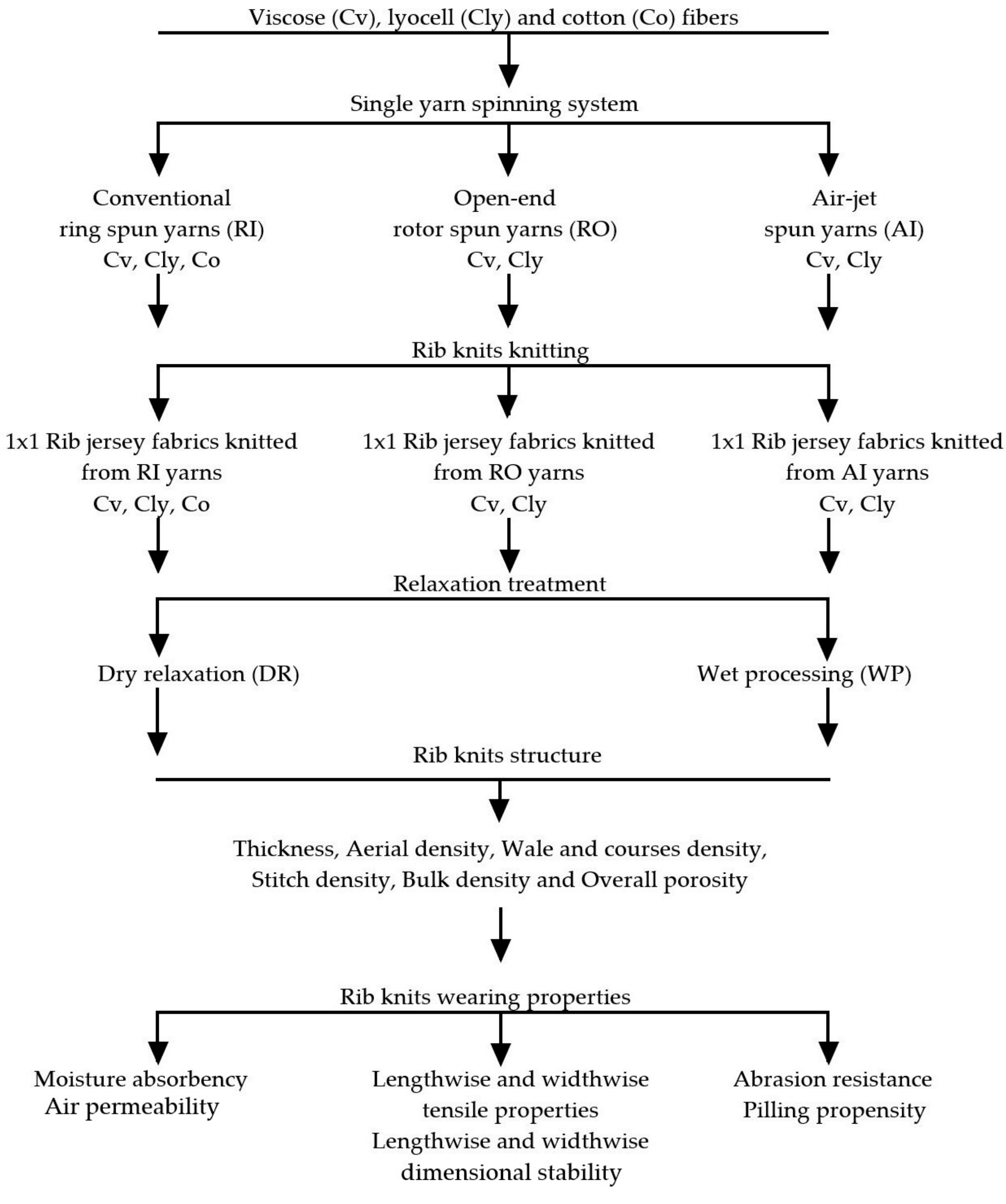


Figure 1. Scheme of the rib knits evaluation methodology.

2.2.1. Structure of 1 × 1 Rib Jersey Fabrics

The 1 × 1 rib jersey fabrics were tested for their thickness, areal density, wale density, course density, stitch density, bulk density, and overall porosity as follows:

- Rib knit thickness, expressed in millimeters, was tested at ten different points using the 2000-U thickness gauge from Hess MBV GmbH, Germany, in accordance with EN ISO 5084:2003 [47]. The pressure used for the measurement was 1 kPa;

- Areal density of rib knit, expressed in grams per square meter, was measured by cutting and weighing five round specimens of 100 square centimeters and multiplying the obtained value by 100, all in accordance with EN 12127:2003 [48];
- Rib knit wale, course, and stitch density, expressed as the number of wales per centimeter, courses per centimeter, and stitches per square centimeter, were determined in accordance with EN 14971:2008, for which five measurements were taken [49];
- Bulk density of rib knit fabrics, expressed in grams per cubic centimeter, was calculated by dividing the areal density and the thickness of the measured fabrics using the following Equation (1):

$$\text{Fabric bulk density } (\text{g}/\text{cm}^3) = \text{Fabric areal density } (\text{g}/\text{m}^2)/1000 \times \text{Fabric thickness (mm)} \quad (1)$$

- Total porosity of the rib knitted fabric, expressed as a percentage, defined as the ratio of the open space (both within and between the yarns) to the total volume of porous material [34,50], was calculated using the following Equation (2):

$$\text{Fabric overall porosity } (\%) = \text{Fiber density } (\text{g}/\text{cm}^3) - \text{Fabric bulk density } (\text{g}/\text{cm}^3)/\text{Fiber density} \times 100 \quad (2)$$

- where the fiber density values used are listed in Table 1.

2.2.2. Wearing Properties of 1 × 1 Rib Jersey Fabrics

The air permeability of rib knits was measured using the Air Tronic Mesdan S.p.A., Italy, air permeability tester in accordance with EN ISO 9237:1995 [51]. The air flow rate through a 5 cm^2 rib knitted surface was recorded ten times under a pressure of 100 Pa, and the air permeability was expressed in cubic decimeters per minute × square centimeter.

To test the moisture absorbency, three circular specimens with an area of 100 cm^2 each were cut per sample. In accordance with ASTM D 2654-89a [52], their weight was measured in the conditioned and absolutely dry state, and the absorbency was calculated according to Equation (3):

$$\text{Moisture absorbency } (\%) = \text{Conditioned weight (g)} - \text{Oven dried weight (g)}/\text{Oven dried weight (g)} \times 100 \quad (3)$$

The tensile properties were tested using the Tensolab 3000 strength tester, Mesdan S.p.A., Italy, in accordance with EN ISO 13934-1:2013 [53]. Five strips in the ribbed knitted fabric were stretched in the lengthwise and widthwise directions (with a clamping size of 200 mm × 50 mm, a pretension of 2 N and a tensile speed of 100 mm/min) until they broke. The breaking strength and elongation at break were recorded and expressed in Newton and percentages, respectively.

The length and width stability of circular rib knitted fabrics was tested after one washing and drying cycle according to EN ISO 6330:2012 [54] under the following conditions: Electrolux Wascator FOM1 CLS, Sweden; mild washing at 40 °C; phosphate-free ECE reference detergent without optical brighteners (SDC Enterprises Limited, Thongsbridge, UK); and air drying. The changes in rib knit dimensions were calculated in accordance with EN ISO 3759:2011 and EN ISO 5077:2008 [55,56] and expressed as a percentage. The percentage change in area dimension was calculated using Equation (4) [29] as follows:

$$\text{Areal dimensional chage } (\%) = \text{Length change} + \text{Width change} - (\text{Length change} \times \text{Width change})/100 \quad (4)$$

The abrasion resistance of the rib knitted fabric was tested using the Martindale abrasion and pilling tester, Mesdan S.p.A., Italy, in accordance with EN ISO12947-2:2016 [57]. For three samples tested, the number of rubs against a reference wool abrasive (SDC Enterprises Limited, UK) was recorded until breakage occurred.

The modified Martindale method according to EN ISO 12945-2:2020 [58] was used to determine the pill formation on the surface of rib knits. Three circular specimens were abraded with the same wool abrasive and pilling was visually assessed by three observers according to EN ISO 12945-4:2020 [59] after the recommended number of pilling rubs. Based on the comparison between abraded and original samples using the reference pilling photo (Roaches SM54 knitted standards, double jersey, UK), ratings from 5 to 1 were assigned (5—no change to 1—severe change).

The average result and standard deviation were calculated for all tests performed, where applicable.

3. Results and Discussion

The results include the evaluation of the structure and wearing properties of two sets of circular 1 × 1 rib jersey fabrics made from three types of differently spun viscose and lyocell yarns after dry relaxation and wet processing, compared to reference cotton rib knits. The applicability of viscose and lyocell fibers in the production of novel knitted fabrics with improved properties for underwear was discussed by analyzing the influence of fiber type, spinning system, and the degree of relaxation of the knitted fabrics on their structure, mechanical, usage, and comfort properties.

3.1. Structure Evaluation of Rib Knits

The results for the thickness, areal density, wale and course density, stitch density, bulk density, and overall porosity of dry relaxed and wet processed 1 × 1 rib jersey fabrics are shown in Table 3.

Table 3. Structural properties of viscose (Cv), lyocell (Cly), and cotton (Co) dry relaxed (DR) and wet processed (WP) rib knits produced from ring (RI), open-end rotor (RO), or air-jet (AI) spun yarns, with the corresponding standard deviation where applicable.

1st Part

1 × 1 Rib Jersey Fabric	Rib Knit Thickness, mm		Rib Knit Bulk Density, g/m^3		Rib Knit Overall Porosity, %	
	DR	WP	DR	WP	DR	WP
RI-Cv	0.61 ± 0.03	0.42 ± 0.01	0.28	0.35	81.40	76.89
RO-Cv	0.65 ± 0.02	0.42 ± 0.01	0.24	0.42	84.15	72.15
AI-Cv	0.81 ± 0.01	0.67 ± 0.01	0.18	0.21	88.16	85.76
RI-Cly	0.84 ± 0.01	0.67 ±0.01	0.20	0.22	86.58	85.78
RO-Cly	0.77 ± 0.02	0.66 ± 0.01	0.19	0.24	87.71	84.42
AI-Cly	0.84 ± 0.02	0.69 ± 0.01	0.17	0.21	88.77	86.38
RI-Co	0.64 ± 0.02	0.66 ± 0.03	0.26	0.27	83.04	82.57

2nd Part

1 × 1 Rib Jersey Fabric	Rib Knit Areal Density, g/m^2		Rib Knit Wale/Course Density, cm^{-1}		Rib Knit Stitch Density, cm^{-2}	
	DR	WP	DR	WP	DR	WP
RI-Cv	170.2 ± 0.9	145.6 ± 1.5	22.0 ± 0.0/12.5 ± 0.5	21.0 ± 0.0/12.5 ± 0.5	275.0	262.5
RO-Cv	154.5 ± 1.1	175.5 ± 0.9	20.0 ± 0.0/12.5 ± 0.5	20.0 ± 0.0/13.5 ± 0.5	250.0	270.0
AI-Cv	143.8 ± 1.3	143.1 ± 1.1	18.0 ± 0.0/12.5 ± 0.5	17.0 ± 0.0/14.0 ± 0.0	225.0	238.0
RI-Cly	171.4 ± 1.5	144.8 ± 1.1	20.5 ± 0.5/12.0 ± 0.0	20.0 ± 0.0/13.0 ± 0.0	246.0	260.0
RO-Cly	143.8 ± 1.7	156.3 ± 1.4	18.0 ± 0.0/13.0 ± 0.0	20.0 ± 0.0/13.0 ± 0.0	234.0	260.0
AI-Cly	143.4 ± 1.1	142.8 ± 1.1	19.0 ± 0.0/13.0 ± 0.0	18.5 ± 0.5/13.0 ± 0.0	247.0	240.5
RI-Co	167.2 ± 1.1	177.2 ± 1.3	21.5 ± 0.5/12.5 ± 0.5	21.0 ± 0.0/13.0 ± 0.0	268.8	273.0

Despite the fact that all rib knitted fabrics were fabricated under the same conditions, using a machine adapted to the parameters of knitting with cotton yarn, the results of their structural properties differ from each other.

3.1.1. Thickness, Bulk Density, and Overall Porosity of Rib Knits

Dry relaxed set of lyocell rib knits are on average thicker (0.84 ± 0.03 mm) compared to viscose knitted fabrics (0.69 ± 0.09 mm) produced from ring, open-end rotor and air-jet yarns. However, there is a significant difference in the thickness of the dry relaxed viscose knit sample produced from air-jet spun yarns (Table 3). After wet processing and full relaxation, the thickness of all knitted samples made from viscose and lyocell fibers decreases. For lyocell knits from differently spun yarns, the variations are minimal and the thickness on average (0.67 ± 0.01 mm) corresponds to the thickness of the cotton reference knit made from ring-spun yarn (0.66 ± 0.03 mm).

Figure 2 shows the percentage change in thickness, bulk density, and overall porosity of the rib knitted fabrics tested after wet processing in relation to the dry relaxed values and their interdependence. The percentage reduction in thickness after wet processing is greater for viscose rib knits (35.38–17.28%) compared to ribbed knits made from lyocell fibers (20.24–14.29%).

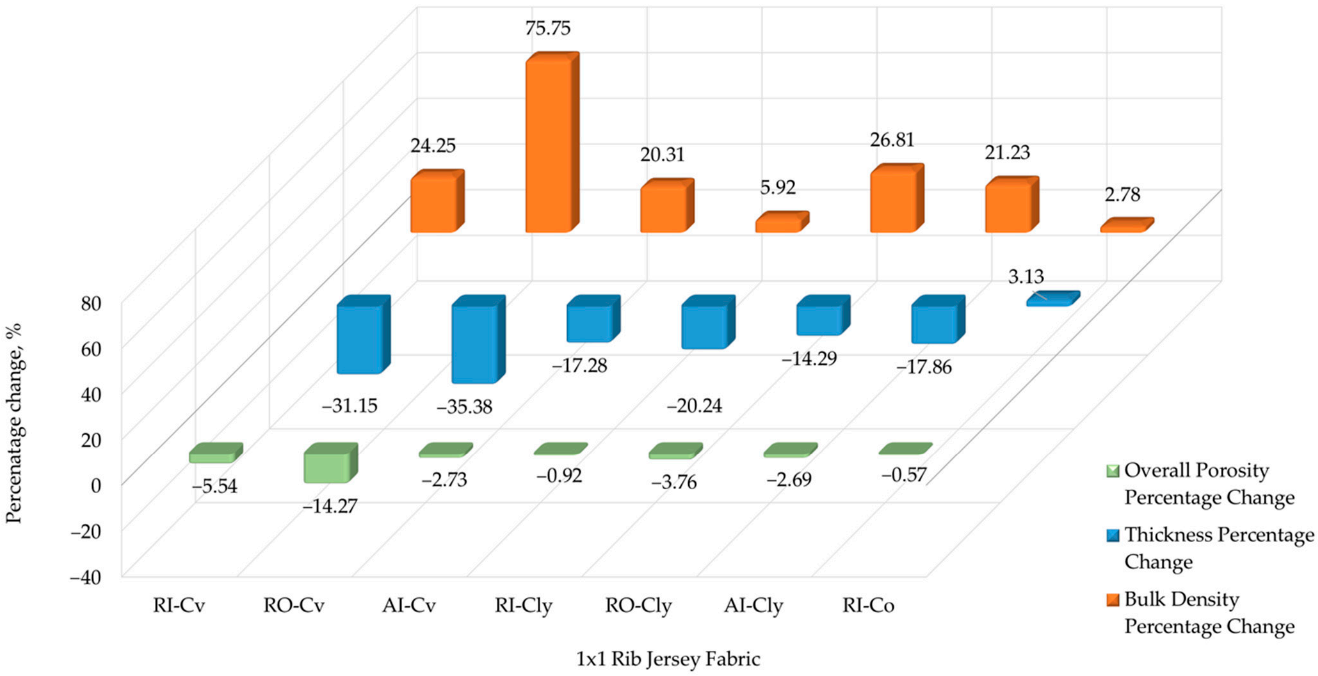


Figure 2. Thickness, bulk density, and overall porosity percentage change of viscose (Cv), lyocell (Cly), and cotton (Co) rib knits after wet processing in relation to dry relaxed values.

The results shown in Table 3 indicate that dry relaxed thicker samples of rib knitted fabrics have lower bulk density values and higher overall porosity, which are directly related to the hairiness of the differently spun yarns (Table 2). It is obvious that the highest determined hairiness of ring-spun yarns (6.47 for viscose and 6.50 for lyocell) causes the highest values for the bulk density of viscose and lyocell knitted fabrics, while the lowest hairiness of air-jet spun yarns (3.75 for Cv and 3.53 for Cly) causes the lowest values for the bulk density of the knitted fabrics. The results of the overall porosity of the rib knitted fabrics are inversely proportional and decreases with increasing yarn hairiness used for their production.

After wet processing, all tested ribbed knit samples are thinner, have a higher bulk density, and lower porosity (Table 3). At the same time, rib knitwear samples made of lyocell fibers have a lower average bulk density (0.22 ± 0.01 g/m^3) and a higher average total porosity (85.53 ± 0.82%) compared to knitted fabrics made of viscose fibers (0.33 ± 0.08 g/m^3 and 78.26 ± 5.64%, respectively), making them more comfortable to wear in direct contact with the skin.

Figure 2 shows that the percentage increase in bulk density after wet processing is greater for the viscose knit samples (20.31–75.75%) compared to the lyocell knit samples (5.92–26.81%). There is also a lower percentage decrease in bulk density for lyocell knitwear (up to 3.76%) compared to viscose knitwear (up to 14.27%). This indicates greater stability and uniformity in the structure of rib knits made from lyocell fibers compared to viscose knits, which can also be associated with a more uniform structure, surface, and cross-sectional shape of lyocell fibers.

3.1.2. Areal Density, Wale and Course Density, and Stitch Density of Rib Knits

In dry relaxed samples of viscose and lyocell rib knits, different values of areal density were obtained within the same set of knits (Table 3 (2nd part)), with the highest value of areal density found in knits made of viscose, lyocell, and cotton ring-spun yarns, which also have the highest surface hairiness (Table 2). After wet processing and full relaxation of the knitted fabric, the areal density of the samples changes. From the results shown in Table 3 (2nd part), it can be seen that it depends directly on the change in the wale and course density of the rib knitted fabrics as well as the irregularity of the yarns, which is greatest for open-end rotor yarns (Table 2). This is reflected in the highest values of areal density recorded for wet-processed viscose and lyocell knitted fabric samples produced from rotor-spun yarns, which also show a percentage increase in areal density compared to the same dry relaxed knitted fabric samples (13.56% and 8.69%), as shown in Figure 3. The areal density of other samples of ribbed knits in the viscose and lyocell series is reduced by wet processing, with only minimal percentage changes recorded for knitted fabrics made from air-jet spun yarns (Figure 3). The areal density of wet processed viscose and lyocell sets is, on average, lower than the areal density of the cotton reference knitted fabric (154.7 ± 14.7 g/m^2, 148 ± 5.9 g/m^2 and 177.2 g/m^2 respectively), with the areal density and thickness of the cotton rib knit increasing after wet processing (Table 3).

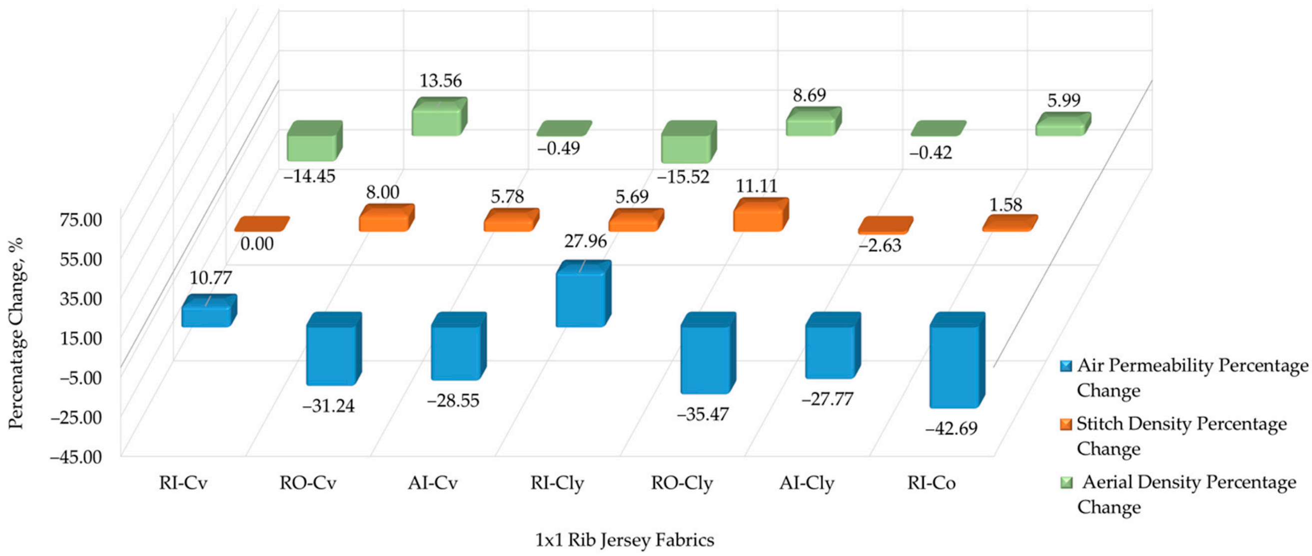


Figure 3. Air permeability, areal density, and stitch density percentage change of viscose (Cv), lyocell (Cly), and cotton (Co) rib knits after wet processing in relation to dry relaxed values.

The wale density of dry relaxed rib knits varies and is between 18/cm and 22/cm for viscose knits, and between 19/cm and 20.5/cm for lyocell knits. In the dry relaxed rib knits, all viscose knit samples and the reference cotton sample had the same value for course density (12.5/cm), while in the lyocell knitted fabrics, the course density was 12/cm for samples produced from ring-spun yarns and 13/cm for samples produced from open-end rotor and air-jet spun yarns. After wet processing, the rib knit wale density generally decreases, except for viscose knit samples made from open-end rotor-spun yarns, where it remains the same, and lyocell knit samples made from open-end rotor-spun yarns, where it increases per unit length. In this context, the course density of rib knitted fabrics generally increases but remains the same for the RI-Cv, RO-Cly, and AI-Cly knit samples, which consequently leads to different dimensional changes in rib knits and different values of stitch density (Table 3 (2nd part)). It should be noted that stitch density/cm^2 generally increases, while a decrease was observed only in the RI-Cv and AI-Cly knit samples. The smallest decrease in stitch density of rib knits after wet processing was observed in lyocell knits made from air-jet yarns (only −2.6% of the wale density), indicating the best structural stability of this knitted fabric (Figure 3).

3.2. Wearing Properties Evaluation of Rib Knits

3.2.1. Air Permeability and Moisture Absorbency of Rib Knits

The results for air permeability and moisture absorbency of dry relaxed and wet processed 1 × 1 rib jersey fabrics are shown in Table 4. In a warm and humid environment, better breathability and moisture absorption lead to a pleasant state of psychological and physical harmony of the person with the underwear-body microclimate [33].

Table 4. Air permeability and moisture absorbency of viscose (Cv), lyocell (Cly), and cotton (Co) dry relaxed (DR) and wet processed (WP) rib knits produced from ring (RI), open-end rotor (RO), or air-jet (AI) spun yarns, with the corresponding standard deviation.

1 × 1 Rib Jersey Fabric	Rib Knit Air Permeability, $dm^3/min\ cm^2$		Rib Knit Absorbency, %	
	DR	WP	DR	WP
RI-Cv	52.47 ± 3.34	58.12 ± 2.83	10.12 ± 1.20	10.05 ± 1.28
RO-Cv	107.90 ± 3.29	74.19 ± 6.08	10.02 ± 1.18	10.31 ± 1.19
AI-Cv	97.31 ± 1.56	69.53 ± 3.22	9.90 ± 1.12	9.77 ± 1.31
RI-Cly	60.66 ± 2.78	77.62 ± 2.84	8.97 ± 1.17	8.83 ± 1.26
RO-Cly	115.83 ± 2.01	74.75 ± 3.85	8.71 ± 1.21	8.60 ± 1.42
AI-Cly	101.61 ± 3.72	73.39 ± 2.81	9.60 ± 1.34	9.42 ± 1.15
RI-Co	49.64 ± 1.84	28.45 ± 3.27	5.78 ± 1.21	6.07 ± 1.35

Despite the fact that air permeability is primarily related to the size and number of pores in the fabrics [33], there is a noticeable dependence on the areal density, stitch density of the rib knit structure (discussed in the previous Section 3.1.2.), and the type of yarn used for manufacturing. Therefore, Figure 3 shows the percentage change in air permeability, stitch density, and areal density of the tested rib knit fabrics after wet processing relative to the dry relaxed values.

Table 4 shows that in the dry relaxed viscose and lyocell rib knit samples, different values for air permeability were found within the same set of knits—with the lowest values in knits with the highest areal density (Table 3 (2nd part)) made from ring-spun yarns with the highest surface hairiness (Table 2), and the highest values in knits made from open-end rotor-spun yarns with the highest overall irregularity. On average, dry relaxed lyocell rib knitted fabrics exhibited better air permeability (92.70 ± 23.39 $dm^3/min\ cm^2$) than viscose knitted fabrics (85.89 ± 24.03 $dm^3/min\ cm^2$) made from ring, open-end rotor, and air-jet yarns, and than reference cotton knitted fabrics (49.64 $dm^3/min\ cm^2$).

After wet processing, the air permeability of the rib knit samples changes, whereby for the same set of knits on average it decreases. At the same time, lyocell rib knits still show better air permeability (75.25 ± 1.76 $dm^3/min\ cm^2$) compared to viscose knitted fabrics (67.28 ± 6.75 $dm^3/min\ cm^2$) produced from different types of yarns, and to the reference cotton knits (28.45 $dm^3/min\ cm^2$). Despite the reduction in the dispersion of the results (standard deviation) within the set of knits made of viscose and lyocell fibers, the changes are not unequivocal. As the areal and stitch density of wet processed rib knitted fabrics made from open-end rotor yarns increase, their air permeability decreases (31.24% for Cv and 35.47% for Cly) (Figure 3), as does that of knitted fabrics made from air-jet spun yarns. In contrast to cotton, the air permeability of rib knitted fabrics made from viscose and lyocell ring-spun yarns increases (10.77% and 27.96%, respectively), primarily due to a significant reduction in the areal density of these knit samples (Figure 3).

Despite the fact that they are all made of cellulose, viscose rib knits showed, as expected, better ability to absorb moisture than lyocell and cotton samples, due to differences in fiber structure and regain (Table 4). At the same time, the dry relaxed set of viscose samples produced from ring, open-end rotor and air-jet yarns had an average absorbency of 10.01 ± 1.12% compared to lyocell (9.09 ± 0.37%) and reference cotton knits (5.78%). It should be noted that the lyocell rib knit made from air-jet spun yarns was found to have a higher absorption capacity of the structure compared to other lyocell samples (9.60%). This indicates greater internal accessibility, which may be related to a more uniform fiber and yarn surface morphology, as well as the highest value of overall porosity found (Table 3). Due to the full relaxation of the knitted fabric, there were only minimal changes in the absorbency of the wet processed samples—for viscose in the range of—0.69% to 2.89%; for lyocell, up to −1.88%; while an increase of 5.02% was recorded for the cotton reference.

3.2.2. Tensile Properties and Dimensional Stability of Rib Knits

The results for the breaking strength and elongation at break of dry relaxed and wet processed 1 × 1 rib jersey fabrics, which were determined for the length and width directions, are shown in Table 5.

Table 5. Lengthwise and widthwise breaking strength and elongation at break of viscose (Cv), lyocell (Cly), and cotton (Co) dry relaxed (DR) and wet processed (WP) rib knits produced from ring (RI), open-end rotor (RO), or air-jet (AI) spun yarns, with the corresponding standard deviation.

1 × 1 Rib Jersey Fabric	Rib Knit Breaking Strength, N				Rib Knit Elongation at Break, %			
	Lengthwise		Widthwise		Lengthwise		Widthwise	
	DR	WP	DR	WP	DR	WP	DR	WP
RI-Cv	304.8 ± 20.6	182.7 ± 18.3	65.1 ± 4.6	60.6 ± 2.1	50.8 ± 0.9	37.7 ± 2.2	131.3 ± 7.1	123.3 ± 5.8
RO-Cv	204.7 ± 12.6	203.0 ± 17.2	64.9 ± 4.1	63.7 ± 5.6	38.1 ± 1.3	47.7 ± 1.5	171.8 ± 5.7	146.1 ± 4.4
AI-Cv	242.9 ± 21.6	146.8 ± 34.8	74.9 ± 2.7	82.8 ± 4.7	44.1 ± 2.7	51.1 ± 3.1	165.7 ± 5.3	119.3 ± 3.0
RI-Cly	418.1 ± 21.2	300.6 ± 28.6	119.2 ± 3.3	120.6 ± 2.6	45.9 ± 1.1	41.2 ± 1.5	180.1 ± 2.0	164.7 ± 4.3
RO-Cly	359.4 ± 19.5	330.9 ± 31.7	105.1 ± 3.1	106.9 ± 2.6	47.0 ± 0.9	49.4 ± 1.2	205.7 ± 2.4	185.8 ± 2.9
AI-Cly	278.0 ± 26.4	205.6 ± 15.2	81.1 ± 2.3	75.1 ± 5.1	45.8 ± 2.2	44.1 ± 2.4	175.7 ± 3.9	120.0 ± 5.0
RI-Co	415.7 ± 42.3	373.8 ± 35.6	121.2 ± 11.6	103.6 ± 13.0	50.6 ± 2.2	56.5 ± 1.3	142.4 ± 3.1	183.3 ± 6.7

The results presented in Table 5 show that the dry relaxed set of ribbed knits made from lyocell fibers has, on average, a higher tensile strength in the lengthwise and widthwise directions (351.8 ± 57.4 N and 101.8 ± 15.7 N) than viscose knits (250.8 ± 41.2 N and 68.3 ± 4.7 N) produced from ring, open-end rotor, and air-jet spun yarns. Higher values for the breaking strength of knitted fabrics were obtained in the length direction, with the highest values found for Cv and Cly samples made from ring-spun yarns, which have better tensile properties (Table 2). At the same time, the breaking strength values of the Ri-Cly knit sample are comparable to those of the Ri-cotton reference.

To substantiate this, representative tensile diagrams obtained with the strip test are shown in Figure 4 for each Cv (Figure 4a,b) and Cly (Figure 4c,d) fabric sample, compared to a cotton reference, separately for the knits' length (i.e., the wale direction) and width (i.e., the course direction). The type of these two diagrams differs, with the higher elastic area being found in knits' elongation in the course direction [45].

After wet processing, changes in the structural parameters, in particular, influence the tensile properties of the knitted fabric. The breaking strength in the lengthwise direction of wet processed knits decreases in all samples and is generally associated with a reduction in wale density. Figure 5 shows the dependence of the percentage change in breaking strength in the lengthwise direction and the wale density of the rib knits tested after wet processing in relation to the dry relaxed values. No significant changes in breaking strength in the opposite direction of the knitted fabrics were observed after wet processing (Table 5).

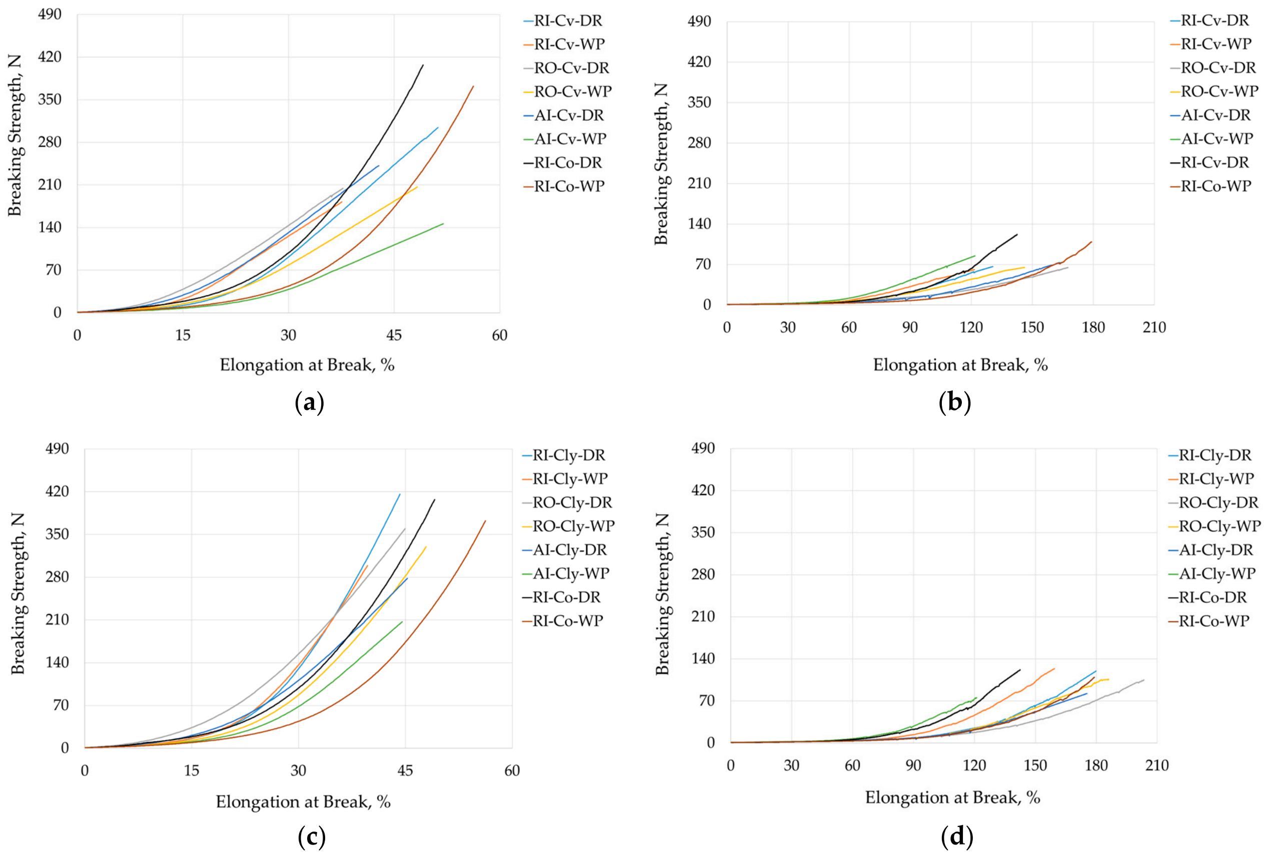


Figure 4. Strength/elongation diagrams of dry relaxed (DR) and wet processed (WP) rib knits produced from ring (RI), open-end rotor (RO), or air-jet (AI) spun yarns made from viscose (Cv) fibers (**a**) in the length and (**b**) in the width direction; lyocell (Cly) fibers (**c**) in the length and (**d**) in the width direction compared to the cotton reference.

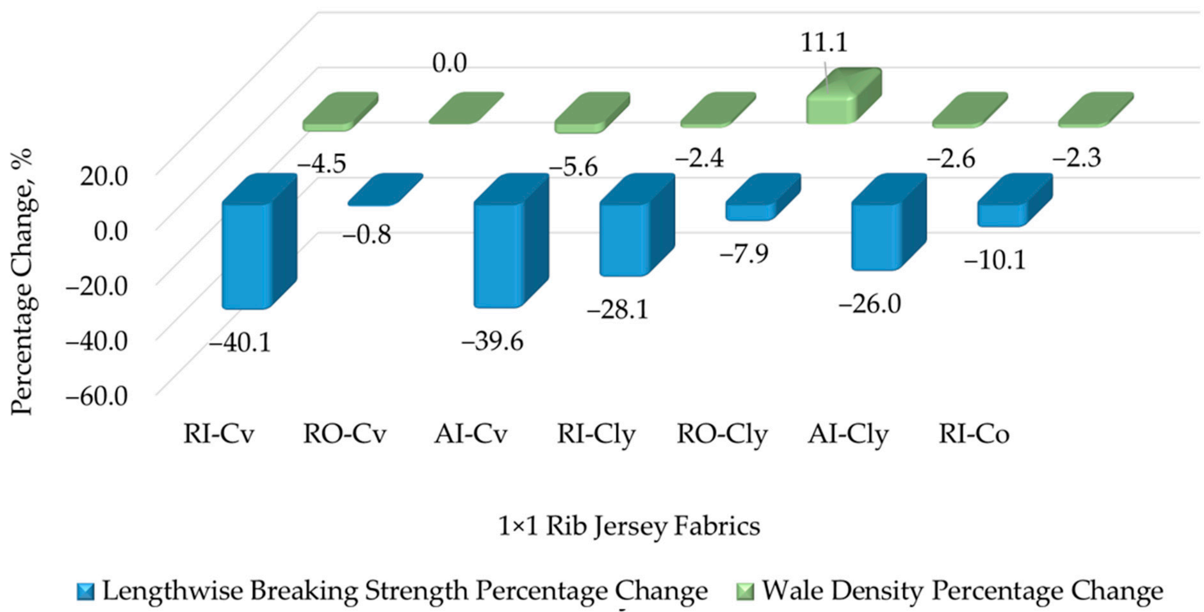


Figure 5. Lengthwise breaking strength and wale density percentage change of viscose (Cv), lyocell (Cly), and cotton (Co) rib knits after wet processing in relation to dry relaxed values.

When analyzing the elongation at break of the tested knit samples, which is shown in Table 5, higher values were found in the width direction than in the length direction. For the dry relaxed and wet processed sets of viscose and lyocell knits, the average values of elongation at break in the lengthwise direction are almost the same for both sets (44.3 ± 5.2% and 45.5 ± 5.7% for viscose; 46.2 ± 0.5% and 44.9 ± 3.4% for lyocell). Since knitted fabrics for underwear generally exhibit up to four times greater elongation at break in the course direction [45], the results shown in Table 5 and Figure 4b,d confirm their applicability, although a certain reduction in the width direction was observed after wet processing (in contrast to the cotton reference). This could be related to the structural changes in the knits after full relaxation during wet processing, in particular a decrease in the wale density (Figure 5) and an increase in course density (shown in Figure 6).

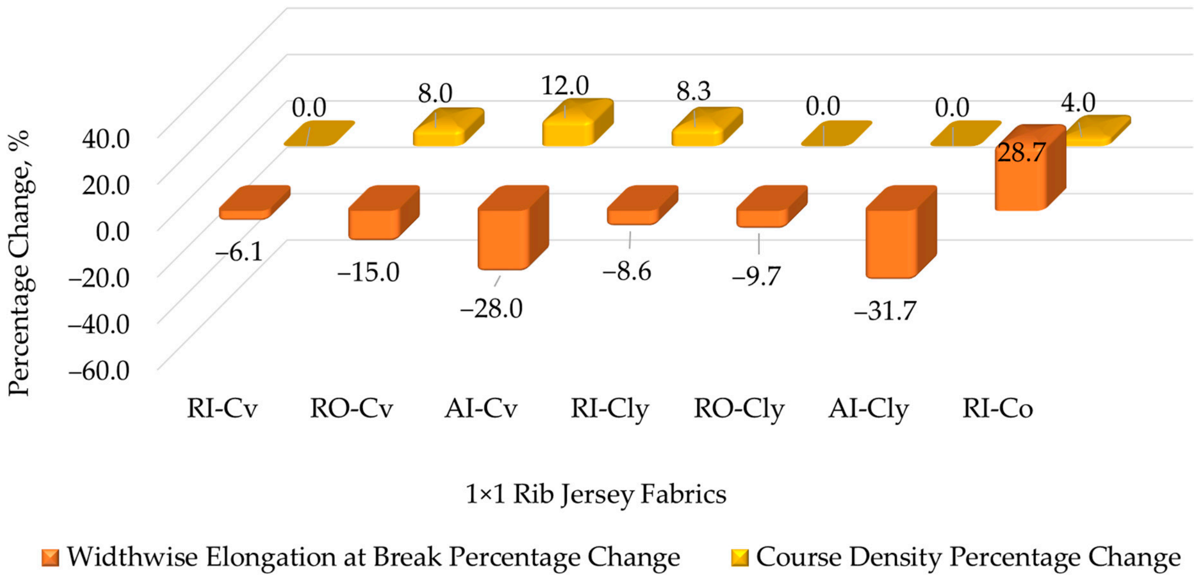


Figure 6. Widthwise elongation at break and wale density percentage change of viscose (Cv), lyocell (Cly), and cotton (Co) rib knits after wet processing in relation to dry relaxed values.

All knitted fabrics are susceptible to deformation [18], especially after washing and drying. The dimensional stability of knitted fabrics is a serious problem because the structure of the fabrics, especially the stitch density, changes [19]. Therefore, the results of the percentage change in length, width, and whole tested area obtained for dry relaxed and wet processed 1 × 1 rib jersey fabrics after a washing and drying cycle are presented in Figure 7.

A dimensional change in the form of shrinkage in the lengthwise direction was observed in all dry relaxed and wet processed rib knit samples (Figure 7a). Lower shrinkage was found in wet processed knits, with lyocell rib knits showing, on average, lower lengthwise shrinkage (−8.1%) than viscose knits (−11.9%) produced from ring, open-end rotor, and air-jet yarns.

Changes in width in rib knits made of viscose fibers are not unambiguous, because in dry relaxed and wet processed knits made of ring and air-jet spun yarns, extension occurs, and thus, the complete deformability of viscose knits (Figure 7b). Despite the fact that there was no change in width in the dry relaxed lyocell knit samples made from ring and air-jet spun yarns, an average shrinkage of −5.6% was observed in all tested knits after complete relaxation in the wet processed knitted fabrics. This is reflected in the calculated results of the shrinkage by area, presented in Figure 7c, which averaged −19.9% for dry relaxed and −14.1% for wet processed rib knitted fabrics made of lyocell fibers, and are comparable to the values determined for the cotton reference (−21% for dry relaxed and −12.0% for wet processed).

Knitted fabrics with rib patterns are more susceptible to major dimensional changes compared to other knits, e.g., single jersey and interlock structures [29], as the results in Figure 7 show. This is due to the fact that the yarns are exposed to high stress factor during the production of the fabric [18] and relax after wet treatment. However, it must also be taken into account that ribbed knitted underwear changes its dimensions depending on body movement, and despite greater shrinkage after washing and drying, has a residual extension when worn.

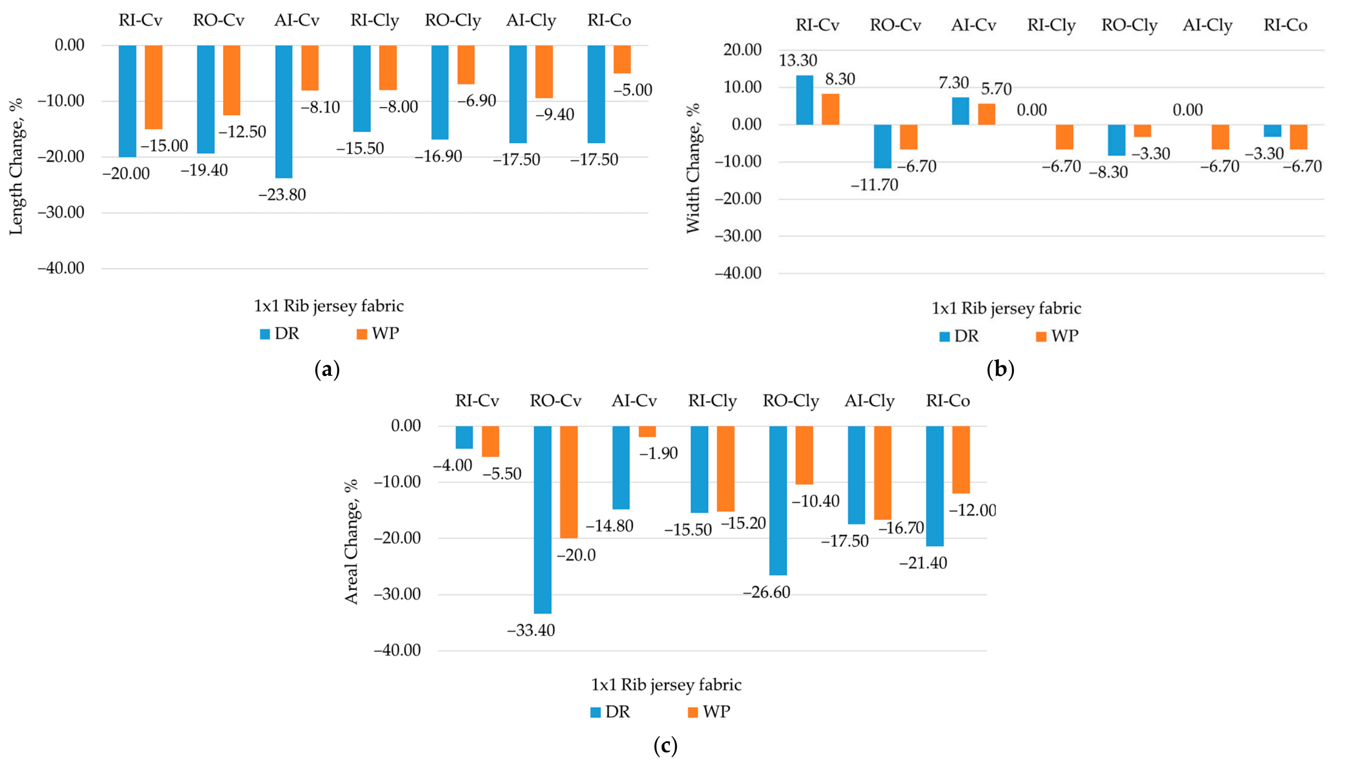


Figure 7. Graphs of: (**a**) lengthwise; (**b**) widthwise; and (**c**) areal dimensional change of viscose (Cv), lyocell (Cly)l and cotton (Co) dry relaxed (DR) and wet processed (WP) rib knits produced from ring (RI), open-end rotor (RO), or air-jet (AI) spun yarns.

3.2.3. Abrasion and Pilling Properties of Rib Knits

The results for the abrasion failure of dry relaxed and wet processed 1 × 1 rib jersey fabrics were shown in Figure 8 and Table 6. They result from the contact forces and consist of a normal load, acting at a right angle to the fabric surface and a frictional force, acting tangentially against the relative movement during wear. The direct effects of these forces are transverse compressive stress and axial shear stress within the fibers and yarns near the surface of the knitted fabric [60]. At the same time, material wears away from the contact surface during rubbing until tensile failure occurs across the reduced fiber and yarn cross-section. In addition, high shear stresses can occur beneath the surface, leading to internal cracks and the failure of fibers and yarns due to splitting and peeling of the surface [60].

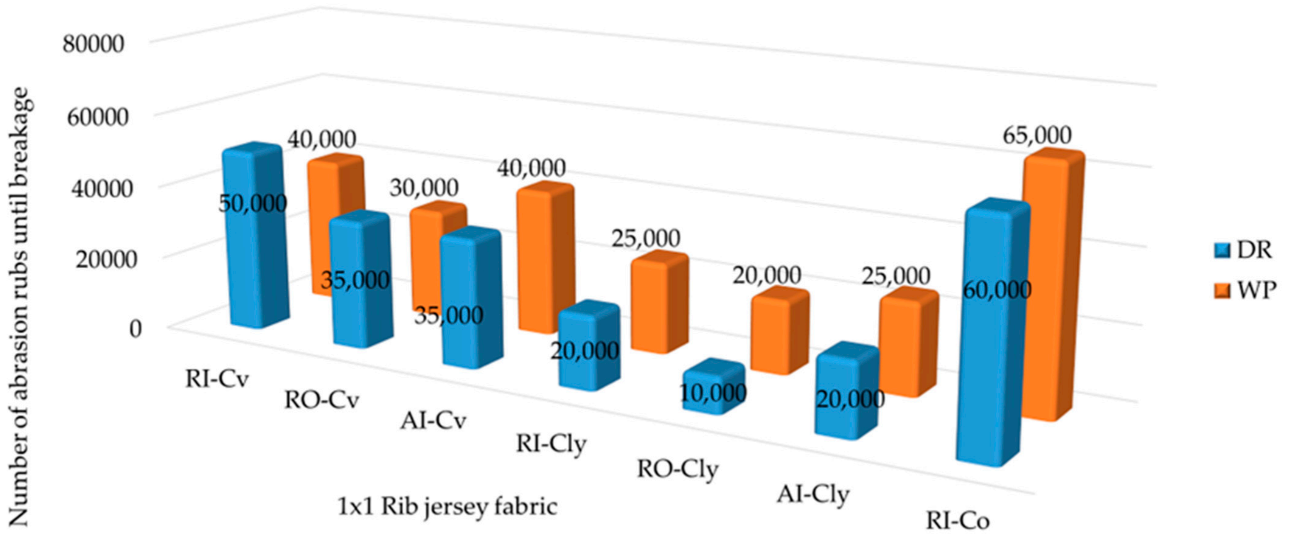
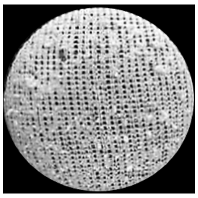
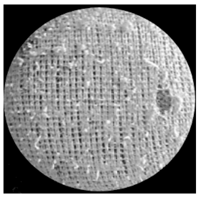
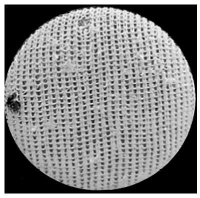
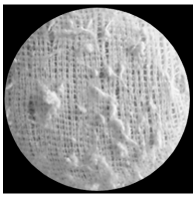
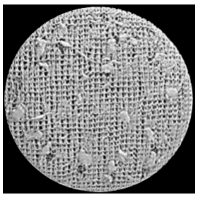
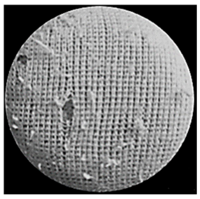
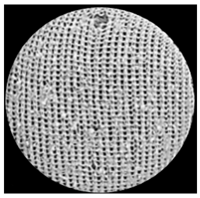
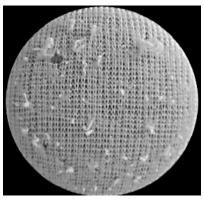
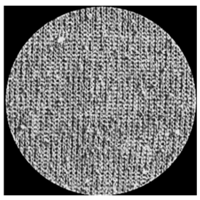
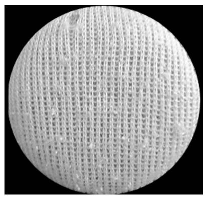
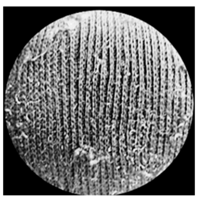
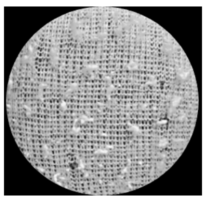
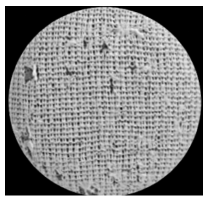


Figure 8. Abrasion resistance of viscose (Cv), lyocell (Cly), and cotton (Co) dry relaxed (DR) and wet processed (WP) rib knits produced from ring (RI), open-end rotor (RO), or air-jet (AI) spun yarns.

Table 6. Surface of the of viscose (Cv), lyocell (Cly), and cotton (Co) dry relaxed (DR) rib knits produced from ring (RI), open-end rotor (RO), or air-jet (AI) spun yarns after breakage.

1 × 1 Rib Jersey Fabric	**RI-Cv-DR**	**RO-Cv-DR**	**AI-Cv-DR**
Dry Relaxed			
RI-Co-DR	**RI-Cly-DR**	**RO-Cly-DR**	**AI-Cly-DR**
			
1 × 1 Rib Jersey Fabric	**RI-Cv-WP**	**RO-Cv-WP**	**AI-Cv-WP**
Wet Processed			
RI-Co-WP	**RI-Cly-WP**	**RO-Cly-WP**	**AI-Cly-WP**
			

Although viscose fibers are considered to have the least abrasion resistance of common textile fibers [61], it was found that dry relaxed rib knits made of viscose fibers break between 35,000 and 50,000 abrasion rubs. Lower abrasion properties were found in dry relaxed lyocell knits (Figure 8), where breakage occurred between 10,000 and 20,000 abrasion rubs. Despite the fact that lyocell fibers and yarns used for knitting have higher tenacity (Tables 1 and 2), lyocell abrasion between the fibers develops splitting into highly fibrillated ends that promote slight surface wear in the knits.

The abrasion resistance changed in all wet processed rib knits. It decreased in rib knitted fabrics made of viscose fibers (up to 10,000 rubs), where breakage occured between 30,000 and 40,000 abrasion rubs, while in lyocell and cotton knits, the number of abrasion rubs until breakage increased (up to 10,000 rubs), reaching 20,000 to 25,000 for lyocell and 65,000 for cotton (Figure 8).

Since wet lyocell fibers have a higher propensity to split and form surface fibrils [62], more fibrillated lyocell fibers adhere to the knitted surface during wet processing, so that the fabric achieve a tighter structure and the movement of the more entangled fibers within the yarn is therefore limited. This has a direct influence on increasing the abrasion resistance of wet processed lyocell knits, whereby the fibrillation behavior of the fibers can be seen as an advantage. The reason for this occurrence may also be related to the more stable structural compactness of wet processed lyocell rib knits (as described in Section 3.1).

The results in Figure 8 show that viscose and cotton knits made from ring-spun yarns have better abrasion resistance. Despite the fact that ring-spun yarns are hairier, they have a higher tenacity (Table 2) and a more compact structure, where the fibers are better twisted on the surface. It was found that surface wear is higher, and therefore, abrasion resistance is lower in Cv and Cly rib knits made from open-end rotor-spun yarns, whoch have lower tenacity (Table 2) and surface compactness.

The specific surface appearance of the tested rib knit samples at the end of the abrasion test is shown in Table 6, where breakages occurred. When analyzing the abraded rib knits, the formation of pills of different shapes and intensities on the surface is noticeable. The intertwined pills, which are largest in cotton, impair the smoothness of the surface, and thus, the wearing properties and aesthetic quality.

The numerical ratings given to the pilling of dry relaxed and wet processed 1 × 1 rib jersey fabrics after visual assessment are shown in Table 7. The pilling formation on the surface of the ribbed knit was more intense after prolonged wear simulation with an increasing number of pilling rubs for all tested knit samples.

Table 7. Pilling ratings assigned after visual assessment of the surface of viscose (Cv), lyocell (Cly), and cotton (Co) dry relaxed (DR) and wet processed (WP) rib knits produced from ring (RI), open-end rotor (RO), or air-jet (AI) spun yarns after an appropriate number of pilling rubs.

1 × 1 Rib Jersey Fabric	Dry Relaxed						Wet Processed					
	Number of Pilling Rubs											
	125	500	1000	2000	5000	7000	125	500	1000	2000	5000	7000
	Pilling Ratings											
RI-Cv	5.0	4.5	3.0	3.0	2.5	2.0	5.0	4.5	3.5	3.0	2.5	2.5
RO-Cv	4.5	4.5	4.5	3.5	3.0	2.5	4.5	4.5	4.0	3.5	3.0	3.0
AI-Cv	4.5	4.5	4.5	4.5	4.0	3.5	5.0	5.0	4.5	4.5	4.0	3.5
RI-Cly	4.5	3.5	3.5	3.0	3.0	2.5	4.5	4.0	3.5	3.5	3.0	2.5
RO-Cly	5.0	4.0	3.5	3.5	3.5	3.0	4.5	3.5	3.5	3.0	2.5	2.5
AI-Cly	5.0	4.5	4.5	4.5	4.0	3.5	4.5	4.5	4.0	3.5	3.0	3.0
RI-Co	4.0	4.0	3.5	3.0	2.5	2.0	4.5	4.5	4.0	3.0	2.5	2.0

All dry relaxed and wet processed viscose and lyocell rib knit samples made from air-jet spun yarns, with a more uniform structure, smooth handle, and the lowest hairiness

(Table 2), showed the lowest tendency to surface pilling and received the best final ratings for pilling (ratings 3 and 3.5). Rib knitted samples produced from open-end rotor-spun yarns showed a moderate tendency to pilling at the end of the test after rubbing 7000 times (ratings 2.5 and 3), while the lowest pilling ratings were found in rib knits made from ring-spun yarns, where ratings of 2 and 2.5 were given for viscose and lyocell knits, and a rating of 2 was given for the cotton reference (Table 7).

4. Conclusions

The use of viscose and lyocell fibers as alternatives to cotton in the production of ribbed knits for underwear and the influence of unconventionally spun yarns on their wearing quality were discussed. To address the issue of the insufficient applicability of the more environmentally friendly lyocell fibers, two sets of dry relaxed and wet processed 1×1 rib jersey fabrics made of viscose and lyocell fibers were compared with conventional cotton reference. As the results show that the rib knitted fabrics differ in their wearing quality, the following conclusions can be drawn.

The relaxation treatment of rib knitted fabrics influences the results achieved. All wet processed, fully relaxed knits are thinner, have a higher bulk density, and lower porosity. At the same time, rib knits made from lyocell fibers have higher porosity, higher air permeability, and lower bulk density, making them more breathable and more comfortable to wear when placed directly on the skin than similar knits made from viscose fibers. They also have a more stable structure, with the lyocell-knitted fabric made from air-jet spun yarns standing out.

The dry relaxed viscose samples have an average moisture absorption of 10.01% compared to lyocell (9.09%) and cotton knits (5.78%), with lyocell rib knits from air-jet spun yarns showing higher absorbency compared to other lyocell samples (9.60%), indicating greater internal accessibility and also providing high contact comfort. Only minimal changes were observed in the absorption capacity of the wet processed samples.

Dry, relaxed rib knits made of lyocell fibers have, on average, higher tensile strength in both directions than viscose knits, whereby the breaking strength values of lyocell knits made from ring-spun yarns are comparable to those of the Ri-cotton reference. Higher values for breaking strength and lower elongation at break were found in the knits' length. In wet processed knitted fabrics, the breaking strength decreases in the lengthwise direction, as does the elongation at break in the widthwise direction, which is mainly due to the structural changes in the knits.

Less shrinkage in the lengthwise direction after washing and drying was observed in wet processed knits, with lyocell samples showing better results on average. Dry relaxed and wet processed viscose knits made from ring and air-jet spun yarns show a widthwise extension (and thus a deformation of the knits), while an average shrinkage of −5.6% was observed in the wet processed lyocell knitted fabrics. This is reflected in the calculated area-related shrinkage results, which are comparable between lyocell and the cotton reference.

Despite the fact that lyocell fibers and yarns used for knitting have higher tenacity, dry relaxed ribbed knits made of viscose fibers show better abrasion resistance. However, the abrasion resistance has changed for all wet processed samples—it decreases for rib knits made of viscose fibers, while the number of abrasion rubs up to breakage increases for lyocell and cotton knitted fabrics, with the knits made of ring and air-jet spun yarns showing better abrasion resistance.

When analyzing the abraded knit surface, the interlaced pills, which are largest in cotton, affect the smoothness of the surface and thus the aesthetic quality of the knits. All dry relaxed and wet processed viscose and lyocell rib knit samples from air-jet spun yarns showed the lowest tendency to surface pilling, while the lowest pilling values were found in the cotton reference.

From this, it can be concluded that the degree of relaxation of knitwear, the type of fiber, and the type of yarn used for the design of novel knits influence the wearing quality of the underwear. Compared with viscose knits, lyocell rib knits have better structural uniformity, tensile properties, dimensional stability, air permeability, lower abrasion resistance, and comparable moisture absorbency and pilling tendency, which confirms their applicability. At the same time, it should be noted that lyocell knits made from air-spun yarns, which have better contact comfort, aesthetics, and usage quality, can be used for the production of finer women's underwear, while lyocell knitted fabrics made from ring-spun yarns are recommended for the production of underwear with better mechanical properties and a longer service life.

In the next study, the properties of rib knits fabricated from modal and micro-modal fibers will be investigated.

Author Contributions: Conceptualization, A.T.; methodology, A.T., J.Ž., and Z.S.; formal analysis, A.T.; investigation, J.Ž. and Z.S.; resources, A.T. and Z.S.; data curation, J.Ž. and Z.S.; writing—original draft preparation, A.T. and J.Ž.; writing—review and editing, A.T., J.Ž., and Z.S.; visualization, A.T. and J.Ž.; supervision, A.T. and Z.S.; project administration, A.T. and Z.S.; funding acquisition, A.T. and Z.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Croatian Science Foundation under project IP-2016-06-5278, "Comfort and antimicrobial properties of textiles and footwear", and by the University of Zagreb under research grant TP 19/24.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data available in a publicly accessible repository.

Acknowledgments: The authors would like to thank Zlatko Vrljičak, PhD, University of Zagreb Faculty of Textile Technology, for his great technical support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Björquist, S.; Aronsson, J.; Henriksson, G.; Persson, A. Textile qualities of regenerated cellulose fibers from cotton waste pulp. *Text. Res. J.* **2018**, *88*, 2485–2492. [CrossRef]
2. Shen, L.; Worrell, E.; Patel, M.K. Environmental impact assessment of man-made cellulose fibres. *Resour. Conserv. Recycl.* **2010**, *55*, 260–274. [CrossRef]
3. Mendes, I.S.F.; Prates, A.; Evtuguin, D.V. Production of rayon fibres from cellulosic pulps: State of the art and current developments. *Carbohyd Polym.* **2021**, *273*, 118466. [CrossRef]
4. Sharma, A.; Nagarkar, S.; Thakre, S.; Kumaraswamy, G. Structure–property relations in regenerated cellulose fibers: Comparison of fibers manufactured using viscose and lyocell processes. *Cellulose* **2019**, *26*, 3655–3669. [CrossRef]
5. Ciechanska, D.; Wesolowska, E.; Wawro, D. An introduction to cellulosic fibres. In *Handbook of Textile Fibre Structure*, 1st ed.; Eichhorn, S.J., Hearle, J.W.S., Jaffe, M., Kikutani, T., Eds.; Woodhead Publishing Limited: Sawston, UK, 2009; Volume 66, pp. 3–61.
6. Wang, S.; Lu, A.; Zhang, L. Recent advances in regenerated cellulose materials. *Prog. Polym. Sci.* **2016**, *53*, 169–206. [CrossRef]
7. Jiang, X.; Bai, Y.; Chen, X.; Liu, W. A review on raw materials, commercial production and properties of lyocell fiber. *J. Bioresour. Bioprod.* **2020**, *5*, 16–25. [CrossRef]
8. Ma, Y.; Rissanen, M.; You, X.; Moriam, K.; Hummel, M.; Sixta, H. New method for determining the degree of fibrillation of regenerated cellulose fibres. *Cellulose* **2020**, *28*, 31–44. [CrossRef]
9. Textile Exchange. Preferred Fiber & Materials Market Report 2022. Available online: https://textileexchange.org/knowledge-center/reports/materials-market-report-2022/ (accessed on 16 May 2024).
10. Kreze, T.; Malej, S. Structural characteristics of new and conventional regenerated cellulosic fibers. *Text. Res. J.* **2003**, *73*, 675–684. [CrossRef]
11. Albrecht, W.; Wulfhorst, B.; Külter, H. Fiber tables according to P.-A. Koch. Regenerated cellulose fibers. *Chem. Fibers Int.* **1991**, *40*, 26–44.
12. Albrecht, W.; Reintjes, M.; Wulfhorst, B. Fiber tables according to P.-A. Koch. Lyocell fibers (Alternative regenerated cellulose fibers). *Chem. Fibers Int.* **1997**, *47*, 298–304.
13. Wulfhorst, B.; Külter, H. Fiber tables according to P.-A. Koch. Cotton. *Chem. Fibers Int.* **1989**, *39*, 12–34.
14. Tomljenović, A.; Živičnjak, J.; Skenderi, Z. Quality Assessment of Socks Produced from Viscose and Lyocell Fibers. *Materials* **2024**, *17*, 1559. [CrossRef]
15. Fatkić, E.; Geršak, J.; Ujević, D. Influence of Knitting Parameters on the Mechanical Properties of Plain Jersey Weft Knitted Fabrics. *Fibres Text. East. Eur.* **2011**, *19*, 87–91.
16. Hashimoto, Y.; Kim, K.O.; Hashimoto, K.; Takatera, M. Effect of Washing and Drying Conditions on Dimensional Change in Various Articles of Knitted Clothing. *J. Fiber Bioeng. Inform.* **2018**, *11*, 227–240. [CrossRef]

17. Ucar, N.; Yilmaz, T. Thermal properties of 1 × 1, 2 × 2, 3 × 3 rib knit fabrics. *Fibres Text. East. Eur.* **2004**, *12*, 34–38.
18. Mikučionienė, D.; Laureckienė, G. The Influence of Drying Conditions on Dimensional Stability of Cotton Weft Knitted Fabrics. *Mater. Sci.-Medzg.* **2009**, *15*, 64–68.
19. Anand, S.C.; Brown, K.S.M.; Higgins, L.G.; Holmes, D.A.; Hall, M.E.; Conrad, D. Effect of Laundering on the Dimensional Stability and Distortion of Knitted Fabrics. *Autex Res. J.* **2002**, *2*, 85–100. [CrossRef]
20. Onal, L.; Candan, C. Contribution of fabric characteristics and laundering to shrinkage of weft knitted fabrics. *Tex. Res. J.* **2003**, *73*, 187–191. [CrossRef]
21. Mikučionienė, D.; Arbataitis, E. Comparative Analysis of the Influence of Bamboo and Other Cellulose Fibres on Selected Structural Parameters and Physical Properties of Knitted Fabrics. *Fibres Text. East. Eur.* **2013**, *21*, 76–80.
22. Badr, A.; Hassanin, A.; Moursey, M. Influence of Tencel/cotton blends on knitted fabric performance. *Alex. Eng. J.* **2016**, *55*, 2439–2447. [CrossRef]
23. Mckinney, M.; Broome, E.R. The effects of laundering on the performance of open-end and ring-spun yarns in jersey knit fabrics. *Tex. Res. J.* **1977**, *47*, 155–162. [CrossRef]
24. Tomljenović, A.; Živičnjak, J.; Mihaljević, I. Usage Durability and Comfort Properties of Socks Made from Differently Spun Modal and Micro Modal Yarns. *Materials* **2023**, *16*, 1684. [CrossRef] [PubMed]
25. Değirmenci, Z.; Coruh, E. The Influences of Loop Length and Raw Material on Bursting Strength Air Permeability and Physical Characteristics of Single Jersey Knitted Fabrics. *J. Eng. Fiber. Fabr.* **2017**, *12*, 43–49. [CrossRef]
26. Chen, L.N.; Kong, F.R.; Xu, R.C. Comparative Study on Mechanical Properties of Jutecell, Cotton and Bamboo Fiber Knitted Fabrics. *Adv. Mat. Res.* **2012**, *627*, 33–36. [CrossRef]
27. Sitotaw, D.B.; Adamu, B.F. Tensile Properties of Single Jersey and 1×1 Rib Knitted Fabrics Made from 100% Cotton and Cotton/Lycra Yarns. *J. Eng.* **2017**, *2017*, 4310782. [CrossRef]
28. Mikučionienė, D. The Dimensional Change of Used Pure and Compound Cotton Knitwear. *Mater. Sci.-Medzg.* **2004**, *10*, 93–96.
29. Manonmani, G.; Vigneswaran, C.; Chandrasekaran, K.; Ramachandran, T. Effect of Ring and Compact Cotton Spun Yarn characteristics on Physical and Comfort Properties of Knitted Fabrics. *Res. J. Text. Appar.* **2013**, *17*, 68–82. [CrossRef]
30. Öner, E.; Atasağun, H.G.; Okur, A.; Beden, A.R.; Durur, G. Evaluation of Moisture Management Properties on Knitted Fabrics. *J. Text. Inst.* **2013**, *104*, 699–707. [CrossRef]
31. Bhattacharya, S.S.; Ajmeri, J.R. Air Permeability of Knitted fabrics made from Regenerated Cellulosic fibres. *Int. J. Eng. Res. Dev.* **2014**, *10*, 16–22.
32. Oglakcioglu, N.; Marmaralı, A. Thermal comfort properties of some knitted structures. *Fibres Text. East. Eur.* **2007**, *15*, 94–96.
33. Özdil, N.; Marmaralı, A.; Kretzschmar, S.D. Effect of yarn properties on thermal comfort of knitted fabrics. *Int. J. Therm. Sci.* **2007**, *46*, 1318–1322. [CrossRef]
34. Stanković, S.B.; Popović, D.; Poparić, G.B. Thermal properties of textile fabrics made of natural and regenerated cellulose fibers. *Polym. Test.* **2008**, *27*, 41–48. [CrossRef]
35. Majumdar, A.; Mukhopadhyay, S.; Yadav, R. Thermal properties of knitted fabrics made from cotton and regenerated bamboo cellulosic fibres. *Int. J. Therm. Sci.* **2010**, *49*, 2042–2048. [CrossRef]
36. Sakthivel, J.; Anbumani, N. Dimensional properties of single jersey knitted fabrics made from new and regenerated celllosic fibers. *J. Text. Appar. Technol. Manag.* **2012**, *7*, 1–10.
37. Rameshkumar, C.; Anandkumar, P.; Senthilnathan, P.; Jeevitha, R.; Anbumani, N. "Comparitive Studies on Ring Rotor and Vortex Yarn Knitted Fabrics. *Autex Res. J.* **2008**, *8*, 100–105.
38. Kireçci, A.; Kaynak, H.K.; Ince, M.E. Comparative Study of the Quality Parameters of Knitted Fabrics Produced from Sirospun, Single and Two-ply Yarns. *Fibres Text. East. Eur.* **2011**, *19*, 82–86.
39. Tripathi, L.; Behera, B.K. Comparative Studies on Ring, Compact and Vortex Yarns and Fabrics. *J. Text. Sci. Fash. Technol.* **2020**, *6*, 1–14.
40. Iqbal, S.; Eldeeb, M.; Ahmad, Z.; Mazari, A. Comparative Study on Viscose Yarn and Knitted Fabric Made From Open End and Rieter Airjet Spinning System. *Tekst. Ve Konfeksiyon* **2017**, *27*, 234–240.
41. Ortlek, H.G.; Onal, L. Comparative study on the characteristics of knitted fabrics made of vortex-spun viscose yarns. *Fibers Polym.* **2008**, *9*, 194–199. [CrossRef]
42. Kim, H.A.; Kim, S.J. Mechanical Properties of Micro Modal Air Vortex Yarns and the Tactile Wear Comfort of Knitted Fabrics. *Fibers Polym.* **2018**, *19*, 211–218. [CrossRef]
43. Erdumlu, N.; Ozipek, B.; Oztuna, A.S.; Cetinkaya, S. Investigation of Vortex Spun Yarn Properties in Comparison with Conventional Ring and Open-end Rotor Spun Yarns. *Text. Res. J.* **2009**, *79*, 585–595. [CrossRef]
44. Tian, H.; Jiang, Y.; Qi, Y.; Xiang, H.; Yan, J. Study of knitted fabrics with ultra-low modulus based on geometrical deformation mechanism. *Text. Res. J.* **2019**, *89*, 891–899. [CrossRef]
45. Kopitar, D.; Pavlović, Ž.; Skenderi, Z.; Vrljičak, Z. Comparison of Double Jersey Knitted Fabrics Made of Regenerated Cellulose Conventional and Unconventional Yarns. *Tekstilec* **2022**, *65*, 25–35. [CrossRef]
46. *EN ISO 139:2005/A1:2011*; Textiles—Standard Atmospheres for Conditioning and Testing. ISO: Geneva, Switzerland, 2005.
47. *EN ISO 5084:2003*; Textiles—Determination of Thickness of Textiles and Textile Products. ISO: Geneva, Switzerland, 2003.
48. *EN 12127:2003*; Textiles—Fabrics—Determination of Mass per Unit Area Using Small Samples. ISO: Geneva, Switzerland, 2003.

49. *EN 14971:2008*; Textiles—Knitted Fabrics—Determination of Number of Stitches per Unit Length and Unit Area. ISO: Geneva, Switzerland, 2008.
50. Camilli Duru, S.; Candan, C. Effect of repeated laundering on wicking and drying properties of fabrics of seamless garments. *Text. Res. J.* **2013**, *83*, 591–605. [CrossRef]
51. *EN ISO 9237:1995*; Textiles—Determination of the Permeability of Fabrics to Air. ISO: Geneva, Switzerland, 1995.
52. *ASTM D 2654-89a*; Standard Test Methods for Moisture in Textiles. ASTM: West Conshohocken, PA, USA, 2021.
53. *EN ISO 13934-1:2013*; Textiles—Tensile Properties of Fabrics—Part 1: Determination of Maximum Force and Elongation at Maximum Force Using the Strip Method. ISO: Geneva, Switzerland, 2013.
54. *EN ISO 6330:2012*; Textiles—Domestic Washing and Drying Procedures for Textile Testing. ISO: Geneva, Switzerland, 2012.
55. *EN ISO 3759:2011*; Textiles—Preparation, Marking and Measuring of Fabric Specimens and Garments in Tests for Determination of Dimensional Change. ISO: Geneva, Switzerland, 2011.
56. *EN ISO 5077:2008*; Textiles—Determination of Dimensional Change in Washing and Drying. ISO: Geneva, Switzerland, 2008.
57. *EN ISO 12947-2:2016*; Textiles—Determination of the Abrasion Resistance of Fabrics by the Martindale Method—Part 2: Determination of Specimen Breakdown. ISO: Geneva, Switzerland, 2016.
58. *EN ISO 12945-2:2020*; Textiles—Determination of Fabric Propensity to Surface Pilling, Fuzzing or Matting—Part 2: Modified Martindale Method. ISO: Geneva, Switzerland, 2020.
59. *EN ISO 12945-4:2020*; Textiles—Determination of Fabric Propensity to Surface Pilling, Fuzzing or Matting—Part 4: Assessment of Pilling, Fuzzing or Matting by Visual Analysis. ISO: Geneva, Switzerland, 2020.
60. Morton, W.E.; Hearle, J.W.S. Flex Fatigue and Other Forms of Failure. In *Physical Properties of Textile Fibres*, 3rd ed.; The Textile Institute: Manchester, UK, 1997; pp. 678–706.
61. Özdil, N.; Özçelik Kayseri, G.; Süpüren Mengüç, G. Analysis of Abrasion Characteristic in Textiles. In *Abrasion Resistance of Materials*; Adamiak, M., Ed.; InTech: Rijeka, Croatia, 2012; pp. 119–146.
62. Karypidis, M.; Wilding, M.A.; Carr, C.M. The Effect of Crosslinking Agents and Reactive Dyes on the Fibrillation of Lyocell. *AATCC Rev.* **2001**, *1*, 40–44.